

DESIGN AND IMPLEMENTATION OF HUMAN CROWD DENSITY
ESTIMATION SYSTEM WITH ENERGY HARVESTING IN
WIRELESS SENSOR NETWORK PLATFORM

by

SOLAHUDDIN YUSUF BIN FADHLULLAH

Thesis submitted in fulfillment of
the requirements for the degree of
Doctor of Philosophy

May 2017

ACKNOWLEDGMENTS

Science is descriptive but not explanatory. Science explains mathematically the behaviour of nature, but it often does not explain why it is so. It is a wonder that the rules of our complex world can be expressed in mathematical terms. Nature seems to present itself in simple numerical ways.

I am purely devoted to the notion that religion and science are at harmony. God made the nature in a level that human minds can comprehend. And God answered the basis of the ‘why’ and ‘what’ questions through religion.

All praise to the One true God; the Most Gracious and Merciful. God, the Creator of all things seen and unseen, the Creator of the biggest of things; the ‘Arsh, to the smallest of things; the quarks?, the Creator of life and death, and Most Supreme is His Knowledge and Power. It is by His Will that I have travelled this journey of knowledge enrichment. And I take this utmost opportunity to thank God.

Peace and blessings upon Prophet Muhammad, the Seal of the Prophets. Prophet Muhammad is a blessing to the entire world. He is a man sent for humans to follow towards the straight path. For if a prophet was sent as an Angel, woe to us for we will not be able to exemplify an essence that is not the same as ours. Such is the Wisdom of God, the All-Knower.

I thank my supervisor, Professor Dr. Widad Ismail and my co-supervisor, Associate Professor Dr. Ahmad Shukri Yahaya for their valuable guidance and advice. I thank my family for their relentless support, especially my dearest wife. My specific heartiest thanks to my parents for literally everything they have given me.

I thank my colleagues, USM and its staff for their assistance. And lastly I thank everyone that has prayed for my success, knowingly or not. May all of us find the light of our lives.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	ix
LIST OF FIGURES	xii
LIST OF ABBREVIATIONS	xvii
ABSTRAK	xx
ABSTRACT	xxii
CHAPTER ONE: INTRODUCTION	
1.1 Background	1
1.2 Problem Statement	3
1.3 Objectives	4
1.4 Research Contributions	5
1.5 Research Scopes	5
1.6 Thesis Layout	6
CHAPTER TWO: LITERATURE REVIEW	
2.1 The Radio Design Problem	7
2.2 Human Crowd Density Estimation	8
2.2.1 Non-Participatory Method: Accuracy and Feasibility	13
2.2.1 (a) Crowd Size-based Algorithm	15
2.2.1 (b) Path loss-based Algorithm	18
2.2.2 Wireless Coverage	20
2.2.3 Human Crowd Properties	22
2.3 Power Issue in Human Crowd Density Estimation System	25
2.3.1 Energy Harvesting	26

2.3.2	Energy Harvesting in Wireless Sensor Network	28
2.3.3	Issues in Developing the Energy Harvesting Mechanism	35
2.4	Summary	36

CHAPTER THREE: METHODOLOGY

3.1	Wireless Sensor Network Platform	40
3.2	Crowd Density Estimation	41
3.2.1 (a)	Algorithm and Estimation Accuracy	43
3.2.1 (b)	Density Classification	44
3.2.1 (c)	Path Loss Model	46
3.2.2	Statistical Methods	47
3.2.2 (a)	One-way Analysis of Variance	47
3.2.2 (b)	Design of Experiments	50
3.2.3	Wireless Range Extension	54
3.3	Energy Harvesting Mechanism	58
3.3.1	System Architecture	58
3.3.2	Solar cell	59
3.3.3	Power Management Unit	61
3.3.4	Maximum Power Point Tracking	67
3.3.5	Storage Element	68
3.3.6	Proposed H-CDE System	71
3.4	Summary	72

CHAPTER FOUR: IMPLEMENTATION AND EXPERIMENTATIONS OF THE PROPOSED SYSTEM

4.1	Part A: Implementation of Human Crowd Density Estimation System	75
4.1.1	Wireless Sensor Network Implementation	76
4.1.2	The Coordinator	80

4.1.3	The End Nodes	85
4.2	Statistical Methods	87
4.2.1	Implementation of One-way Analysis of Variance	87
4.2.2	Implementation of Design of Experiments	88
4.3	Part B: Implementation of Energy Harvesting Mechanism	89
4.3.1	End Node Power Management Unit	90
4.3.2	Energy Harvesting Design Optimizations	95
4.4	Part C: Experimentation	101
4.4.1	Calibration	101
4.4.2	Stability and Specification Adherence	105
4.4.2 (a)	Latency	105
4.4.2 (b)	Throughput	110
4.4.2 (c)	Self-healing	111
4.4.2 (d)	Antenna Radiation Pattern	113
4.4.2 (e)	Outdoor Range Test	114
4.4.2 (f)	The Effect of Voltage on RF Transmission	116
4.4.2 (g)	Current and Power Consumption	118
4.4.2 (h)	Crowd Density Estimation Accuracy	119
4.4.3	Energy Harvesting Performance	121
4.4.3 (a)	Effect of Solar Cell Alignment	121
4.4.3 (b)	Maximum Power Point Tracker	123
4.4.3 (c)	Energy Harvesting Mechanism Functionality Test	125
4.4.3 (d)	Energy Harvesting Performance in Range Test	126
4.4.3 (e)	Battery Performance	127
4.4.3 (f)	Over- and Under-voltage Protection	128
4.4.3 (g)	Power Efficiency	129
4.4.3 (h)	Energy Harvesting Performance in Actual Deployment	130
4.5	Summary	130

CHAPTER FIVE: RESULTS AND DISCUSSIONS

5.1	Wireless Sensor Network-Radio Frequency Performance Evaluation	132
5.1.1	Calibration	132
5.1.2	Stability and Functionality	136
5.1.2 (a)	Latency	136
5.1.2 (b)	Throughput	144
5.1.2 (c)	Network Self-healing	146
5.1.2 (d)	Antenna Radiation Pattern	148
5.1.2 (e)	Range Test	152
5.1.2 (f)	The Effect of Voltage on RF Transmission	155
5.1.2 (g)	Current and Power Consumption	157
5.2	Human Crowd Density Estimation Evaluation	158
5.2.1	One-way Analysis of Variance	159
5.2.1 (a)	Main Findings	159
5.2.1 (b)	Residuals	161
5.2.2	Design of Experiment	161
5.2.2 (a)	Analysis of the P -values	162
5.2.2 (b)	Main Factor Influencing Signal Attenuation	164
5.2.2 (c)	Interaction factors influencing signal attenuation	165
5.2.2 (d)	Residuals	167
5.2.3	Crowd Density Estimation Classification	168
5.3	Energy Harvesting Performance Evaluation	177
5.3.1	Effect of Solar Cell Alignment	177
5.3.2	Maximum Power Point Tracker	179
5.3.3	Energy Harvesting Performance of the Tags	180
5.3.4	Energy Harvesting Performance in Range Test	183
5.3.5	Battery Performance	185
5.3.6	Over- and Under-voltage Protection	187

5.3.7	Power Efficiency	189
5.3.8	Energy Harvesting Performance in Crowds	190
5.3.8 (a)	Battery Charging	190
5.3.8 (b)	Voltage and Current of H-CDE End Nodes	192
5.3.8 (c)	Power Output	194
5.4	Comparison of the Proposed H-CDE System with the Previous Approaches	195
5.5	Chapter Summary	197

CHAPTER SIX: CONCLUSION

6.1	Conclusion	200
6.2	Suggestions for Future Work	201

REFERENCES	203
-------------------	-----

APPENDICES

Appendix A:	Planck-Einstein Relation
Appendix B:	Quantum Field Theory
Appendix C:	Capacitor versus Battery (Density)
Appendix D:	BQ25504 Power Management Unit
Appendix E:	ZigBee PHY and MAC layer frame
Appendix F:	ZigBee Network layer and APS data frame
Appendix G:	Arduino UNO
Appendix H:	API source code of the Training Phase
Appendix I:	Source code for the Monitoring Phase
Appendix J:	Bill of Materials of the H-CDE Tag
Appendix K:	DOE Template
Appendix L:	SMD Circuit Design for the H-CDE Tag
Appendix M:	A Small Improvement in the BQ25504 Design

LIST OF PUBLICATIONS

LIST OF TABLES

		Page
Table 2.1	Related works on the RF-based H-CDE systems	10
Table 2.2	Related studies that depended on Bluetooth device detection	11
Table 2.3	Related parameters on non-participatory H-CDE system	14
Table 2.4	Comparison between wireless standards for H-CDE	21
Table 2.5	A list of RF-based research on human crowd properties	23
Table 2.6	Power solution for non-participatory H-CDE systems	26
Table 2.7	Energy harvesting sources and their capabilities	27
Table 2.8	Related works on energy harvesting nodes	29
Table 2.9	Performance comparison between the supercapacitor and li-ion battery at high capacity. A tick ($\sqrt{}$) indicates better performance	30
Table 2.10	Features available on the Smartmode	33
Table 2.11	Availability of WSN, EH and H-CDE elements in related works	36
Table 2.12	Best features on current systems. (Colour code: blue for H-CDE and red for power / EH)	38
Table 3.1	Functionality of the Coordinator and End Node of the WSN	41
Table 3.2	Comparison between the proposed H-CDE system with other related works	42
Table 3.3	Density classification by Yuan, Zhao, Qiu and Xi (2013)	45
Table 3.4	Justification for the statistical methods conducted	48
Table 3.5	Selection guide for DOE	51
Table 3.6	Factors and levels of the DOE test	52
Table 3.7	The features on three types of Xbee products	55
Table 3.8	Main specification of the Xbee S2B PRO and S2 module (international variant) (Digi, 2015)	56
Table 3.9	Specification of the ZigBee, Wi-Fi and Bluetooth standards	57
Table 3.10	Solar cells specification	60
Table 3.11	Voltage regulation methods and the related works	61
Table 3.12	PMU protection methods and the related works	62

Table 3.13	Commercial PMU for solar EH. The green cells indicate matching parameters to the Xbee module whereas the reds indicate unsuitability to the load. Colorless cells signify decent PMU to load matching.	63
Table 3.14	Energy density to weight ratio of different rechargeable battery chemistry	69
Table 3.15	Li-ion battery specification	71
Table 3.16	Feature comparison between the proposed H-CDE system compared to related works	72
Table 3.17	Summarized design methods of the proposed system	73
Table 4.1	ZigBee API frame of the Coordinator	78
Table 4.2	Specification of the Coordinator's Xbee module	79
Table 4.3	Xbee module specification of the H-CDE End Nodes	80
Table 4.4	Factors affecting the EH performance of the End Node	94
Table 4.5	Voltage versus capacity for two types of 1000 mAh battery	98
Table 4.6	Voltage regulation methods on the 1000 mAh battery	99
Table 4.7	Related works on 802.15.4 and ZigBee single hop latency. Maximum payload of an 802.15.4 frame is 100 bytes as opposed to 84 bytes for the ZigBee protocol.	107
Table 4.8	Related works on single hop throughput	110
Table 4.9	Crowd Density Classification	120
Table 4.10	Characteristics of the solar cell for the alignment test	123
Table 5.1	Transmission power level comparison between the official documentation and the actual measurement seen at the spectrum analyser. The highlighted box shows the best performing power level.	133
Table 5.2	Power loss incurred by Cable 1	133
Table 5.3	Transmit power versus power levels of the prototype and standalone system	135
Table 5.4	Average latency of Xbee modules when tested in standalone and H-CDE prototype systems	136
Table 5.5	Average voltage of each RF module in router (standalone) and end node. Each End Node has different battery voltage, resulting in the difference of voltage between them.	139
Table 5.6	Single versus two hop latency. Router to end node and Coordinator to end node have similar latency due to absence of sleep mode at one end.	141

Table 5.7	Average throughput of several works compared to the measured	146
Table 5.8	The time taken to self-heal the connections to Router 1, End Node 1, End Node 2 and End Node 3	147
Table 5.9	The parameters versus RSSI using shunt resistor method with VS = 3.296 V	156
Table 5.10	Current consumption of the load and PMU	157
Table 5.11	One-way ANOVA results from Minitab	159
Table 5.12	Values obtained from the DOE section	168
Table 5.13	Extrapolated average RSSI values for the crowd from 20 up to 50 people. σ represents the standard deviation	170
Table 5.14	Prediction accuracy of the proposed H-CDE versus other models	171
Table 5.15	The H-CDE results of related algorithms mapped to the crowd density classification defined by Yuan, Zhao, Qiu and Xi (2013)	172
Table 5.16	Density classification of related works mapped to the guideline provided by Hiroi, Shinoda and Kawaguchi (2016)	173
Table 5.17	Relevant parameters for the modelling	175
Table 5.18	Percentage error of the models compared to the actual data (the lower the better)	176
Table 5.19	The 2000 mAh battery capacity with the initial voltage at 3.61 V	185
Table 5.20	Conditions of the over- and under-voltage protection mechanism	187
Table 5.21	Parameters of the power efficiency experiment	190
Table 5.22	Comparison between the proposed H-CDE with selected works. (Colour code: blue for WSN, red for H-CDE and green for EH)	197
Table 5.23	Overall specification of the H-CDE system	199

LIST OF FIGURES

		Page
Figure 2.1	Block diagram of the SCPL algorithm by Xu et al. (2013)	15
Figure 2.2	Block diagram of the WB algorithm by Yuan, Zhao, Qiu and Xi (2013)	16
Figure 2.3	Block diagram of the EFE algorithm by Xi et al. (2014)	17
Figure 2.4	Exponential fit for the data on signal loss versus crowd size provided by Haochao et al. (2015)	19
Figure 2.5	Density classification (top) and people count (bottom) provided by Hiroi, Shinoda and Kawaguchi (2016)	20
Figure 2.6	System architecture of an EH node	28
Figure 3.1	Overall research approach for the proposed H-CDE system	39
Figure 3.2	Centralized WSN deployment	40
Figure 3.3	Layout comparisons. The layouts of Xi et al. (2014) and Hiroi, Shinoda and Kawaguchi (2016) were not illustrated as the information was not made available.	42
Figure 3.4	Comparison between the algorithms of (a) related works with (b) the proposed H-CDE system	43
Figure 3.5	RF Module selection methodology for wireless range extension	54
Figure 3.6	Block diagram of the proposed system design architecture of the H-CDE node	59
Figure 3.7	(a) Functional Diagram of BQ25504 (Texas Instruments, 2012) and (b) the schematic diagram of the BQ25504 PMU	65
Figure 3.8	Flowchart of the boost converter operation	66
Figure 3.9	The I-V relationship for maximizing power in solar cell	67
Figure 3.10	The MPPT operation of the BQ25504 IC	68
Figure 4.1	Proposed H-CDE system design structure	74
Figure 4.2	Overview of the proposed H-CDE system implementation. The green, red and blue arrows indicate the crowd density estimation, energy harvesting and embedded system segments respectively.	75
Figure 4.3	Address assignment to each End Node (EN)	76
Figure 4.4	(a) XCTU firmware selection and (b) configuration window	79
Figure 4.5	Block diagram of the H-CDE Coordinator	81

Figure 4.6	The H-CDE Coordinator	81
Figure 4.7	Schematic diagram of the Coordinator	82
Figure 4.8	The proposed API functions for the Coordinator	82
Figure 4.9	Flowchart of the operation of the proposed H-CDE Coordinator	83
Figure 4.10	Developed pseudo-code for the Training Phase	84
Figure 4.11	Developed pseudo-code for the Monitoring Phase	85
Figure 4.12	H-CDE End Nodes	86
Figure 4.13	End Node schematic diagram	86
Figure 4.14	Implementation of the statistical methods in the H-CDE system	87
Figure 4.15	The measurement setup where (a) all the people are static and (b) the human crowd is moving about within the stipulated area	88
Figure 4.16	Setup of the DOE at the survey site	89
Figure 4.17	Programming the BQ25504 IC for the H-CDE End Node	92
Figure 4.18	The parameters and PMU status of the H-CDE End Node	93
Figure 4.19	H-CDE End Nodes with solar cells attached	94
Figure 4.20	(a) Over-voltage at RF module due to mismatching of solar cell and (b) the proposed solution adopted by the H-CDE system	96
Figure 4.21	Direct connection from the Xbee to the spectrum analyser through an RP-SMA connector using Connector 1	102
Figure 4.22	Experimental setup for measuring the power loss of the power divider	103
Figure 4.23	The arrangement for measuring the power loss incurred by Cable 1	103
Figure 4.24	Equipment arrangement for measuring transmission power with respect to power level. The dipole antenna is connected directly to the power divider without any cables.	104
Figure 4.25	The relative positions of the factors affecting latency	105
Figure 4.26	The arrangement of the single hop latency test	108
Figure 4.27	Aerial view of the two hops latency test arrangement captured from Google Maps	109
Figure 4.28	Latency test from the Coordinator to the End Node with and without the crowd (top)	109
Figure 4.29	Node arrangement for self-healing where C, R1, EN1, EN2 and EN3 represent the Coordinator, Router 1, End Node 1, 2 and 3 respectively.	112

	The dashed outline of R1 indicates disconnection resulting in the loss connections of the EN from C.	
Figure 4.30	Network Working Mode and Node Discovery feature	113
Figure 4.31	Whip antenna radiation pattern which resembles a doughnut shape	114
Figure 4.32	Experimental setup of the antenna radiation pattern	114
Figure 4.33	The End Node and standalone taped to the car	115
Figure 4.34	Conceptual illustration of the range test	115
Figure 4.35	Stability test hardware setup. VIN is the input voltage while VRF is the voltage at the Xbee module.	116
Figure 4.36	Experiment setup for resistance stability test	117
Figure 4.37	Measuring the current using shunt resistor ($R1 = 1\ \Omega$) method at the End Node	118
Figure 4.38	Conceptual illustration of the solar cell alignment test	121
Figure 4.39	The makeshift solar tracker with a 500 mW solar cell for an initial test	122
Figure 4.40	Angle of inclination of the IXYS solar cells	123
Figure 4.41	Circuit diagram of (a) non-MPPT versus (b) MPPT. The blue rectangle highlights the amendments made to disable the MPPT.	124
Figure 4.42	Block diagram of the MPPT versus non-MPPT experimental setup. A0 is the analogue input pin of the Aduino UNO board.	125
Figure 4.43	Experimental setup for the EH functionality investigation	126
Figure 4.44	Setup for EH range test	126
Figure 4.45	The block diagram of the battery charging without the load experiment	128
Figure 4.46	The setup for over- and under-voltage protection experiment (Texas Instruments, 2012; Texas Instruments, 2013b)	128
Figure 4.47	Power efficiency test (Texas Instruments, 2013b)	130
Figure 5.1	Power losses at each segment based on equation 4.7	134
Figure 5.2	Spectrum analyser calibration measurement	134
Figure 5.3	Transmit and receive timestamps generated in Docklight	137
Figure 5.4	Transmit and sleep cycle for End Node 1	138
Figure 5.5	Comparison between the latency of the H-CDE system with the literature	139

Figure 5.6	Two hop latency	141
Figure 5.7	H-CDE latency model comparison. R stands for router and EN for end node	143
Figure 5.8	Latency of crowded versus empty area. The curves are smoothened using Akima spline fitting.	145
Figure 5.9	Point-to-point throughput with and without the presence of crowd	145
Figure 5.10	The two features utilized for measuring the self-healing time. The network topology is verified in the Networking Working Mode.	148
Figure 5.11	The H-plane radiation pattern of the standalone and End Node (tag)	149
Figure 5.12	The H-CDE node in the PC-ABS casing. The top cover of the casing is not shown.	150
Figure 5.13	The E-plane radiation pattern of the standalone and prototype system	151
Figure 5.14	Radiation pattern NLOS due to obstructions	151
Figure 5.15	Average RSSI versus distance of end nodes with 100 % packet transmission	152
Figure 5.16	XCU Range Test. The local and remote RSSI are for the Coordinator and end node transmission side respectively.	153
Figure 5.17	Range test results in log-distance	154
Figure 5.18	Performance of End Node and Router voltages versus RSSI	155
Figure 5.19	Power generated by solar cell versus H-CDE front-end power usage	158
Figure 5.20	Individual Value Plot of Static Human Crowd and End Node (S) and Dynamic Human Crowd and Static End Node (DS)	160
Figure 5.21	(a) Residuals versus Fits and (b) Normal Plot of Residuals for the S and DS scenarios	161
Figure 5.22	The P-values from the analysis of variance for RSSI (average) using adjusted sum of squares for tests	162
Figure 5.23	Second iteration of ANOVA for the RSSI (average) using adjusted sum of squares for tests	163
Figure 5.24	Mains Effect Plot of crowd size, crowd pattern and number of receiver	164
Figure 5.25	Interaction Plot for the RSSI (a) A combination of the human crowd size and number of receiver and (b) A combination of the human crowd pattern with number of receiver.	166
Figure 5.26	Residual plot for (a) normal probability and (b) versus fits	167
Figure 5.27	Classifying the density of the experimental data where each rhombus	170

represents the average of 10 RSSI measurements. The horizontal lines show the prediction threshold of each technique that separate between low, medium and high density. The vertical lines indicate the density region of the proposed H-CDE. The high density threshold of all the models is the same as $H-CD_{EHD}$.

Figure 5.28	Comparison between the H-CDE prediction model with the actual and other models.	176
Figure 5.29	Voltage and current versus angle in solar cell alignment test	178
Figure 5.30	Battery charging performances subjected to MPPT and non-MPPT (nMPPT)	180
Figure 5.31	Battery charging of nodes under direct sunlight from 3.0 to 3.6 V	181
Figure 5.32	RSSI of nodes for the duration of the experiment	182
Figure 5.33	End Node outdoor operation for five days (120 hours)	183
Figure 5.34	Signal strength versus distance of Router 1 and End Node 3. The End Node with both battery and solar cell connected is labelled as batt_solar. The End Node without battery and solar cell is denoted as wo_batt and wo_solar respectively. The voltage of the End Node versus distance is also shown.	184
Figure 5.35	The duration to charge the batteries to 3.60 V	186
Figure 5.36	Input versus output voltage for the over-voltage protection mechanism	188
Figure 5.37	Battery voltage of each End Nodes and their corresponding curve fits	191
Figure 5.38	Input voltage, VIN, battery voltage, VBAT and battery current flow, IBAT for (a) End Node 2 and (b) End Node 3	193
Figure 5.39	The direction of the current flow determines the positive or negative value of the current recorded by the data logger	194
Figure 5.40	Power output approximation of End Node 2 and 3	195

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
APS	Application Support Sub-layer
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
AT	Transparent
BLE	Bluetooth Low Energy
BMS	Battery Management System
CSI	Channel State Information
CSMA-CA	Carrier Sense Multiple Access - Collision Avoidance
DMM	Digital Multimeter
DOE	Design of Experiments
DSSS	Direct Sequence Spread Spectrum
DS	Dynamic Human Crowd and Static Receiver
EH	Energy Harvesting
EM	Electromagnetic
EN	End Node
ETSI	European Telecommunications Standards Institute
FHSS	Frequency Hoping Spread Spectrum
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
H-CDE	Human Crowd Density Estimation
HD	High Density
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
IC	Integrated Circuit

ICNIRP	International Commission on Non-Ionizing Radiation Protection
ID	Identification
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
I-V	Current versus Voltage
LD	Low Density
Li-ion	Lithium ion
LAN	Local Area Network
LOS	Line-of-Sight
LQI	Link Quality Indicator
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MD	Medium Density
MPPT	Maximum Power Point Tracking
MSK	Minimum-shift Keying
MTU	Maximum Transmission Unit
NLOS	Non-Line-of-Sight
ODFM	Orthogonal Frequency Division Multiplexing
PAN	Personal Area Network
PC	Personal Computer
PC-ABS	Polycarbonate - Acrylonitrile Butadiene Styrene
PHY	Physical
PMU	Power Management Unit
PSDU	Physical Service Data Unit
PV	Photovoltaic
QFN	Quad-Flat No-Leads

RF	Radio Frequency
RFID	Radio Frequency Identification
RP-SMA	Reverse Polarity-SubMiniature version A
RSSI	Received Signal Strength Indicator
RTOS	Real-Time Operating System
RX	Receiver
S	Static Human Crowd and Receiver
SCPL	Sequential Counting, Parallel Localizing
SD	Secure Digital
SPI	Serial Peripheral Interface
S1	Series 1
S2	Series 2
T-R	Transmitter and Receiver
TX	Transmitter
UART	Universal Asynchronous Receiver/Transmitter
USA / US	United States of America
USB	Universal Serial Bus
WBAN	Wireless Body Area Network
Wi-Fi	Wireless Fidelity
WISP	Wireless Identification and Sensor Platform
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

**REKA BENTUK DAN IMPLEMENTASI SISTEM PENGANGGARAN
KEPADATAN MANUSIA DENGAN PENUAIAN TENAGA DALAM PLATFORM
RANGKAIAN PENGESAN TANPA WAYAR**

ABSTRAK

Kepadatan yang tinggi dalam khalayak ramai boleh menjadi berbahaya kerana wujudnya potensi untuk pergerakan sekumpulan manusia secara tiba-tiba yang menyebabkan rempuhan dalam kes kecemasan. Untuk mengurangkan kecederaan mahupun kehilangan nyawa dalam kemalangan yang berkaitan dengan isu kepadatan manusia, sistem pengawasan kepadatan manusia berdasarkan frekuensi radio telah dibangunkan sebagai satu alat keselamatan. Sistem yang didapati pada masa kini mempunyai keupayaan pengawasan yang terhad; saiz pengawasan khalayak yang rendah, jarak pengesanan yang rendah, keperluan bilangan alat komunikasi yang tinggi dan jangka hayat operasi yang terhad. Faktor-faktor ini memberi kesan secara langsung kepada unsur praktikal dan ketepatan sistem penganggaran kepadatan manusia tersebut. Untuk mengurangkan kelemahan keupayaan pengawasan, satu sistem untuk mengesan kepadatan khalayak diusulkan berdasarkan kepada teknologi ZigBee dan rangkaian pengesan tanpa wayar yang meningkatkan jarak pengesanan khalayak kepada 30 m dengan hanya satu nod diperlukan setiap 37.5 m^2 . Hal ini dicapai tanpa mengurangkan bilangan khalayak (50 orang) yang boleh dikesan oleh sistem. Untuk menambahbaik ketepatan anggaran, kesan khalayak terhadap isyarat diselidik menggunakan kaedah statistik 'One-way Analysis of Variance' dan 'Design of Experiments'. Hasil dapatan mengesahkan saiz khalayak memberi kesan yang paling besar terhadap kelemahan isyarat. Untuk interaksi di antara sifat-sifat khalayak, didapati saiz khalayak bersama bilangan alat penerima dan bentuk khalayak bersama bilangan alat penerima memberi kesan signifikan terhadap kekuatan isyarat. Faktor-faktor ini kemudian dimasukkan ke dalam algoritma H-CDE yang diusulkan. Algoritma pengesanan khayalak ini dan pengelasannya menunjukkan purata sebanyak 71.2 peratus ketepatan dalam mengenalpasti tahap kepadatan khalayak yang juga

dapatan terbaik berbanding algoritma lain. Untuk mengatasi masalah kuasa yang terhad, mekanisma tuaian tenaga solar diperkenalkan ke dalam sistem H-CDE untuk memanjangkan jangka hayat operasi pengawasan. Kajian menunjukkan mekanisma tuaian tenaga ini mampu untuk memanjangkan operasi sistem pengawasan secara berterusan jika sistem ini mendapat paling kurang 5 hingga 6 jam pendedahan kepada sinaran matahari setiap 33 jam kitaran. Sumbangan kajian ini ialah pada penambahbaikan sistem berdasarkan teknologi frekuensi radio untuk mengesan kepadatan khalayak, penambahbaikan pada ketepatan penganggaran kepadatan khalayak yang didokongi oleh analisis statistik dan lanjutan operasi sistem melalui mekanisma tuaian tenaga.

DESIGN AND IMPLEMENTATION OF HUMAN CROWD DENSITY ESTIMATION SYSTEM WITH ENERGY HARVESTING IN WIRELESS SENSOR NETWORK PLATFORM

ABSTRACT

A crowd with high density can be dangerous due to the potential of a sudden surge of large moving bodies causing stampede in cases of emergencies. To mitigate casualties in crowd-related disaster, radio frequency-based crowd density estimation and monitoring system is being developed as a safety tool. Current systems have limited monitoring capabilities; low size of crowd monitored, low detection range, high number of transceivers required and finite operational lifetime. These factors directly influence the practicality and prediction accuracy of the system. To mitigate the limited sensing capability, a human crowd density estimation (H-CDE) system based on ZigBee and wireless sensor network technology is proposed that increases the crowd detection range to 30 m with only one transmission node required every 37.5 m². This is achieved without sacrificing the amount of crowd detectable by the system (50 people). To improve the estimation accuracy, the effect of crowd on signal propagation is investigated using One-way Analysis of Variance and Design of Experiments statistical methods. The results verified that the crowd size significantly affects the signal attenuation. In the interactions between the crowd properties, crowd size * number of receiver and crowd pattern * number of receiver were found to significantly affect signal propagation. These factors are then integrated into the proposed H-CDE algorithm. The H-CDE algorithm and its crowd classification yielded an average of 71.2 % accuracy in identifying the level of crowd density, which is the best compared to other algorithms found in the literature. To solve the finite power problem, a solar energy harvesting mechanism is introduced into the H-CDE system to extend the operation of the monitoring system. It is demonstrated that the proposed energy harvesting mechanism could operate perpetually, given that the system is exposed to good sunlight at least for 5 to 6 hours

in every 33-hour cycle. The contribution of the research is on the improved RF-based crowd density detection system, improved crowd estimation accuracy which is backed by statistical analysis and extension of its operations through the energy harvesting mechanism.

CHAPTER ONE

INTRODUCTION

1.1 Background

Human crowd density estimation (H-CDE) is used to predict the magnitude of human concentration in an area. Understanding about the crowd itself is known as crowd science, whereas the estimation effort is an engineering problem and agenda. A highly crowded area has great potential for injuries and accidents. Thus, H-CDE is important to manage human safety and reduce crowd-related disasters.

Conventional H-CDE systems are based on visuals captured from CCTV. The problem with CCTV is that it is resource extensive in terms of labour and financial cost. On the other hand, radio frequency (RF)-based crowd monitoring system could complement the existing system by offering automated and flexible operation.

Crowd density estimation using RF is less developed compared to visual-based systems due to problems related to the unpredictable wireless medium. The wireless medium is susceptible to white noise; random signals where all possible frequencies are present in the atmosphere, which may qualitatively and quantitatively affect a transmission. The behavior of wireless propagation in the shape of reflection, diffraction and scattering, in addition to absorption and multipath, has also created significant problems and challenges to overcome.

Improved techniques have been developed that shows that the RF-based crowd estimation is feasible. The works of Morrison, Bell and Chalmers (2009), Mowafi, Zmily, Abou-Tair and Abu-Saymeh (2013), Yuan, Zhao, Qiu and Xi (2013), Weppner and Lukowicz (2013), Xu et al. (2013), Weppner, Lukowicz, Blanke and Troster (2014), Xi et al. (2014), Yuan (2014), Haochao et al. (2015) and Hiroi, Shinoda and Kawaguchi (2016) on H-CDE is examined. Furthermore, as the H-CDE system requires wireless sensing, the Wireless Sensor Network (WSN) platform is normally adopted as the foundation of the